Measuring $\mathcal{B}(\text{K}^0_\text{L} \to \text{K}^\pm e^\mp \nu)$ with KOPIO

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Abstract

I studied KOPIO's ability to detect $\text{K}^0_\text{L} \to \text{K}^\pm e^\mp \nu$ with the FastMC. $\text{K}^0_\text{L} \to \text{K}^\pm e^\mp \nu$ followed by $\text{K}^+ \to \pi^+ \pi^0$ has relatively unique signature in the detector although it has the same final state as the more copious $\text{K}^0_\text{L} \to \pi^0 \pi^\pm e^\mp \nu$. Assuming the background is dominated by $\text{K}^0_\text{L} \to \pi^0 \pi^\pm e^\mp \nu$ and the trigger efficiency for $\text{K}^0_\text{L} \to \text{K}^\pm e^\mp \nu$ is of order unity, in principle KOPIO could make a measurement of $\mathcal{B}(\text{K}^0_\text{L} \to \text{K}^\pm e^\mp \nu)$ with a precision of 1%. Such a measurement could be turned into a measurement of the neutral to charged kaon mass difference of ~ 10 keV.

1 Introduction

Observing the beta decay of the K^0_L is the dream of many kaon physicists [1]. The branching fraction $\text{K}^0_\text{L} \to \text{K}^\pm e^\mp \nu$ is proportional to $|V_{ud}|^2$ and Δ^5 where $\Delta \equiv M(\text{K}^0_\text{L}) - M(\text{K}^+)$. Using current values of these and other constants gives $\mathcal{B}(\text{K}^0_\text{L} \to \text{K}^\pm e^\mp \nu) = 1.08 \times 10^{-8}$. A 1% measurement of $\mathcal{B}(\text{K}^0_\text{L} \to \text{K}^\pm e^\mp \nu)$ yields an uncertainty on Δ of ~ 10 keV which would be a substantial improvement on the current value of $\Delta = 3995 \pm 34$ keV [2]. Even a less precise measurement would be interesting because the mass difference has never been directly measured.

One way for KOPIO to detect $\text{K}^0_\text{L} \to \text{K}^\pm e^\mp \nu$ is via the subsequent decay $\text{K}^+ \to \pi^+ \pi^0$. The neutral pion can be reconstructed as for $\text{K}^0_\text{L} \to \pi^0 \nu \bar{\nu}$ since the K^+ has nearly the same momentum as the K^0_L . The main background is $\text{K}^0_\text{L} \to \pi^0 \pi^\pm e^\mp \nu$ which has the same final state and $\mathcal{B}(\text{K}^0_\text{L} \to \pi^0 \pi^\pm e^\mp \nu) = (5.18 \pm 0.29) \times 10^{-5}$ [2]. However, $\text{K}^0_\text{L} \to \text{K}^\pm e^\mp \nu$ decays can be distinguished from $\text{K}^0_\text{L} \to \pi^0 \pi^\pm e^\mp \nu$ since the two-body $\text{K}^+ \to \pi^+ \pi^0$ gives a peak in $E^*(\pi^0)$, the electron energy in $\text{K}^0_\text{L} \to \text{K}^\pm e^\mp \nu$ is very small and the opening angle between the neutral and charged pion is small for $\text{K}^0_\text{L} \to \pi^0 \pi^\pm e^\mp \nu$. $\text{K}^0_\text{L} \to \pi^0 \pi^\pm e^\mp \nu$ dynamics suppress the case where the e and ν are produced at rest.

2 Methodology

I generated 1×10^5 $\text{K}^0_\text{L} \to \text{K}^\pm e^\mp \nu$ decays and 2.8×10^6 $\text{K}^0_\text{L} \to \pi^0 \pi^\pm e^\mp \nu$ decays with the FastMC in the Z range (815,1415) cm with the Z of the decay region (1015-1415) cm using the Zeller preradiator (PR) model. $\text{K}^0_\text{L} \to \text{K}^\pm e^\mp \nu$ decays are generated using

phase space while the correct matrix element for $K_L^0 \to \pi^0 \pi^\pm e^\mp \nu$ is used. Neutral pion candidates are reconstructed in the same way as for $K_L^0 \to \pi^0 \nu \bar{\nu}$ analysis although the photon conversion probability in the PR is not taken into account. The reconstructed four-momenta of the neutral pion candidates is transformed to the center-of-momentum system assuming a K_L^0 mass and the usual microbunch structure. The reconstructed K_L^0 vertex is required to be in the range $1065 < Z < 1415$ cm. The lab energy of the $e^\pm$ $E(e)$ and the impact position of the $\pi^\pm$ are assumed to be known precisely. For the evaluation of the angle between the π^0 and the $\pi^\pm$, the direction of the $\pi^\pm$ is calculated using the reconstructed K_L^0 decay vertex and the $\pi^\pm$ impact position. In the case of $\pi^\pm$ decay-in-flight, the impact position is taken as the impact position of the daughter $\mu^\pm$.

I assume a total K_L^0 flux for KOPIO of 1.27×10^{15} K_L^0 exitting the spoiler. This corresponds to 70TP/spill, 12000 hours and a single K_L^0 decay in the decay region per spill. Unless otherwise stated, all histograms are in numbers of expected events for this exposure.

3   Results

Figure 1 shows the reconstructed center-of-momentum energy of the neutral pion for $K_L^0 \to K^\pm e^\mp \nu$ and $K_L^0 \to \pi^0 \pi^\pm e^\mp \nu$ decay. As shown in Figure 2, the tails of the $E^*(\pi^0)$ distribution are greatly reduced by requiring the probability of χ^2 for the fit to the K_L^0 vertex is required to be > 0.001. Figure 3 shows the electron energy *vs* the reconstructed center-of-momentum energy of the neutral pion for $K_L^0 \to K^\pm e^\mp \nu$ and $K_L^0 \to \pi^0 \pi^\pm e^\mp \nu$ decay. Figure 4 shows the cosine of the angle between the $\pi^\pm$ and the π^0 *vs* the electron energy for $K_L^0 \to K^\pm e^\mp \nu$ and $K_L^0 \to \pi^0 \pi^\pm e^\mp \nu$ decay.

Figure 5 shows the cuts used to select signal in the plane of the cosine of the angle between the $\pi^\pm$ and the π^0 *vs* the electron energy. Figure 6 shows the results for the three cuts shown in Figure 5. The key to rejecting $K_L^0 \to \pi^0 \pi^\pm e^\mp \nu$ is to veto on electron energy above ~ 10 MeV and require a significant opening angle between the $\pi^\pm$ and the π^0. The $E^*(\pi^0)$ distribution for $K_L^0 \to K^\pm e^\mp \nu$ has a mean of 246 MeV and a width of 10 MeV. The signal region $220 < E^*(\pi^0) < 270$ MeV was chosen to be approximately 2.5σ about the mean, but with the requirement that the edge of the signal region corresponds to the histogram bin edges. The background in the signal region is estimated from a gaussian fit in the range $190 < E^*(\pi^0) < 300$ MeV because it gives a fairly good representation of the shape of the background. For the results shown, the statistical precision on $\mathcal{B}(K_L^0 \to K^\pm e^\mp \nu)$ is $\sim 1\%$ and the resulting precision on Δ is < 10 keV.

4   Discussion

The requirement of both photons converting the preradiator would reduce the calculated yields by approximately $\times 0.6$.

Other potential backgrounds are $K_L^0 \to \pi^0 \pi^0$ with $\pi^0 \to \gamma e^+ e^-$ and $K_L^0 \to \pi^0 \pi^+ \pi^-$. For $K_L^0 \to \pi^0 \pi^0$ with $\pi^0 \to \gamma e^+ e^-$, the electron or positron must be mistaken for a charged pion or muon. Assuming a photon veto inefficiency of 10^{-3} the effective branching fraction is $\sim 2 \times 10^{-8}$ and time-of-flight requirements as well as kinematics

would probably reduce the rate sufficiently. $K_L^0 \to \pi^0\pi^+\pi^-$ is unlikely to be a background because $E^*(\pi^0)$ is restricted to be less than ~ 190 MeV which is over 5 standard deviations from the $K_L^0 \to K^\pm e^\mp \nu$ peak. In addition one of the charged tracks must be undetected which would offer a suppression of at least 10^4. Assuming 10^4 suppression from $E^*(\pi^0)$ resolution gives an effective $K_L^0 \to \pi^0\pi^+\pi^-$ branching fraction of $\sim 1 \times 10^{-9}$.

I assumed that K^+ could propagate from 200 cm upstream of the decay region. I don't know what effect the field of the final sweeping magnet would have on the these K^+.

In Jaap's Technote [3], he states that the K^+ flux at the entrance to the decay region is 10^{-7} of the K_L^0 flux, although for his small statistics the events are outside the beam hole. Andrei reached a similar conclusion in [4]. If the trajectories of these K^+ are not sufficiently diverted from the K_L^0 beam envelope then such K^+ are a potential source of background. This background could be suppressed by requiring $K_L^0 \to K^\pm e^\mp \nu$ candidates to come from within the K_L^0 beam envelope and/or by making a more stringent requirement on the reconstructed $Z(K)$. Alternatively, this K^+ background could probably be measured by reducing the magnetic field and comparing the increase in rate to predictions from simulation.

I have ignored the possibility that the impact position information of the π could be supplemented by angular information in the case where the π strikes the preradiator or by time-of-flight information.

One of the largest potential effects is suppression of these decays by the trigger, but even if the trigger efficiency is $\mathcal{O}(0.1)$, the statistical precision on Δ is comparable to the current world average.

Of course to obtain a 1% measurement on $\mathcal{B}(K_L^0 \to K^\pm e^\mp \nu)$ would require knowledge of the acceptance and K_L^0 flux to less than 1% which may be difficult.

5 Acknowledgements

I thank all the KOPIOns that I subjected to my rantings about $K_L^0 \to K^\pm e^\mp \nu$. Persistent questions from Laur Littenberg finally prompted me to show that the analysis was viable.

References

[1] L. Littenberg, private communication.

[2] K. Hagiwara *et al.*, Phys. Rev. **D66** 010001 (2002).

[3] J. Doornbos, *Photons, protons and kaons for case 4* KOPIO TN085 29 Apr 2004.

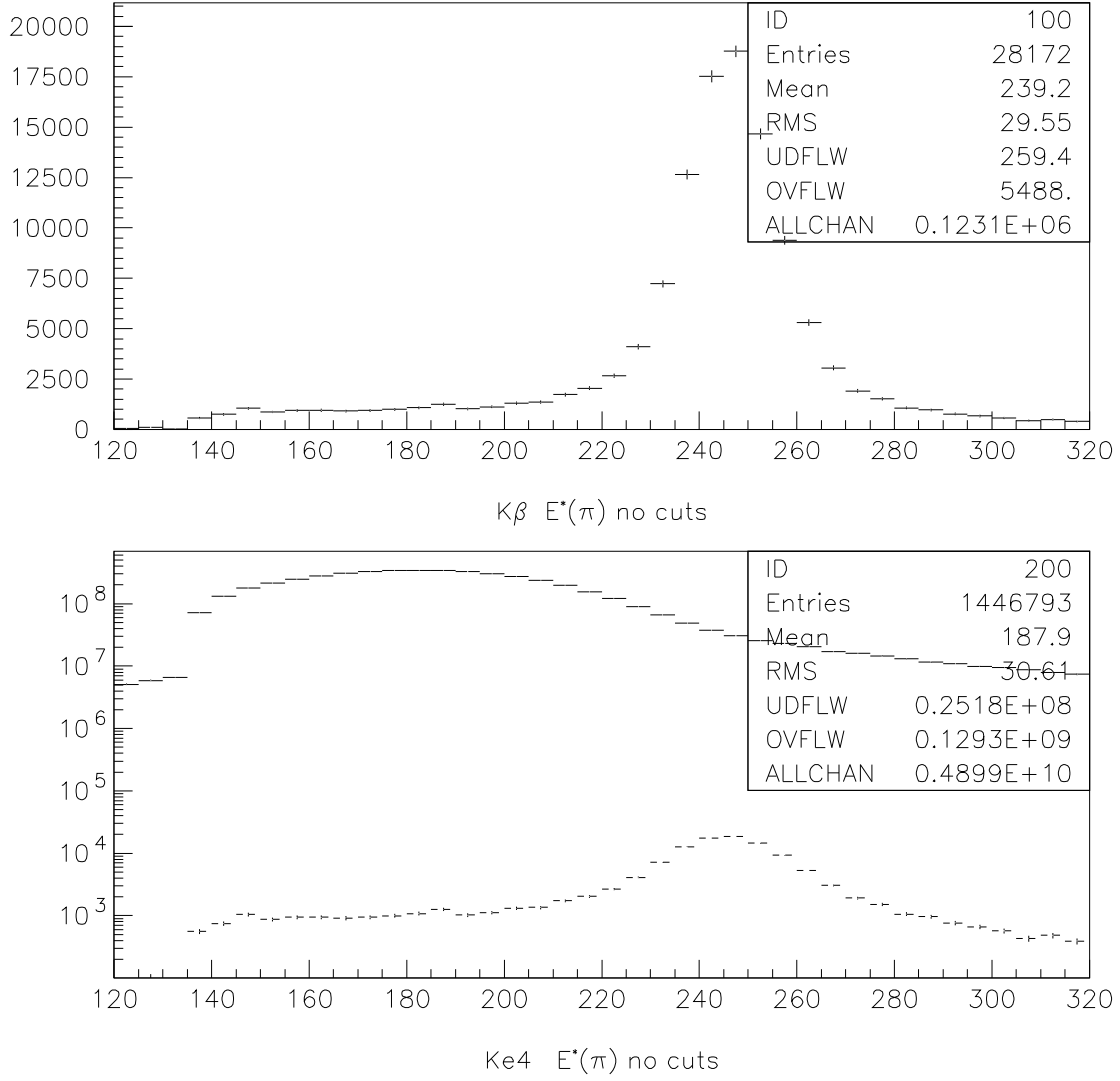[4] A.A. Poblaguev, *Charged kaon production in collimators*, 20 November 2001, http://pubweb.bnl.gov/users/e865/www/KOPIO/Collimators/note111801.ps.

Figure 1: Upper: $E^*(\pi^0)$ distribution for $K_L^0 \to K^\pm e^\mp \nu$ decays. Lower: $E^*(\pi^0)$ distribution for $K_L^0 \to \pi^0 \pi^\pm e^\mp \nu$ ($K_L^0 \to K^\pm e^\mp \nu$) decays as solid (dashed). The reconstructed K_L^0 vertex is required to be in the range $1065 < Z < 1415$ cm. No other cuts are applied.
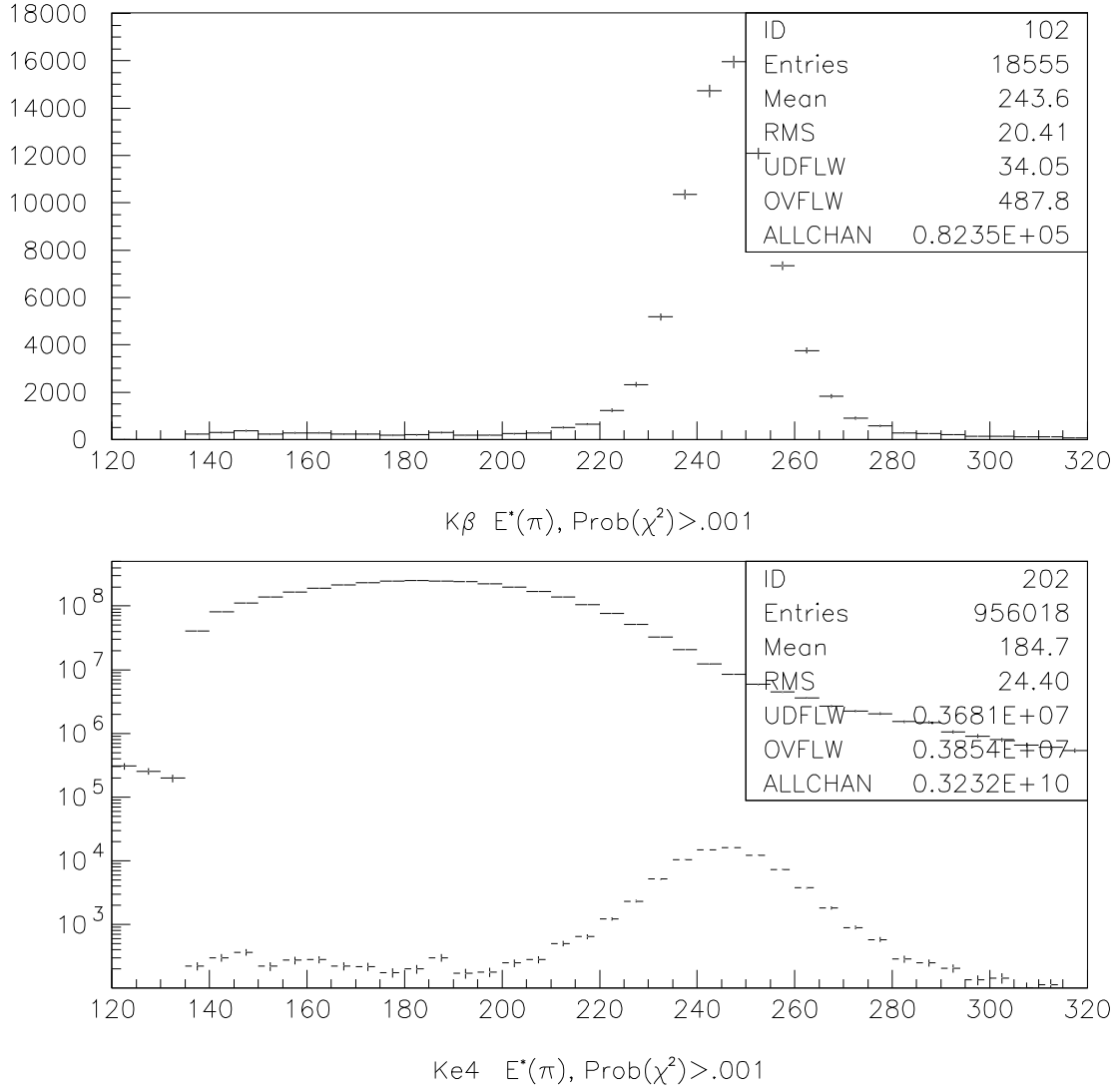
Figure 2: Upper: $E^*(\pi^0)$ distribution for $K_L^0 \to K^\pm e^\mp \nu$ decays. Lower: $E^*(\pi^0)$ distribution for $K_L^0 \to \pi^0 \pi^\pm e^\mp \nu$ ($K_L^0 \to K^\pm e^\mp \nu$) decays as solid (dashed). The reconstructed K_L^0 vertex is required to be in the range $1065 < Z < 1415$ cm. The probability of χ^2 for the fit to the K_L^0 vertex is required to be > 0.001. No other cuts are applied.
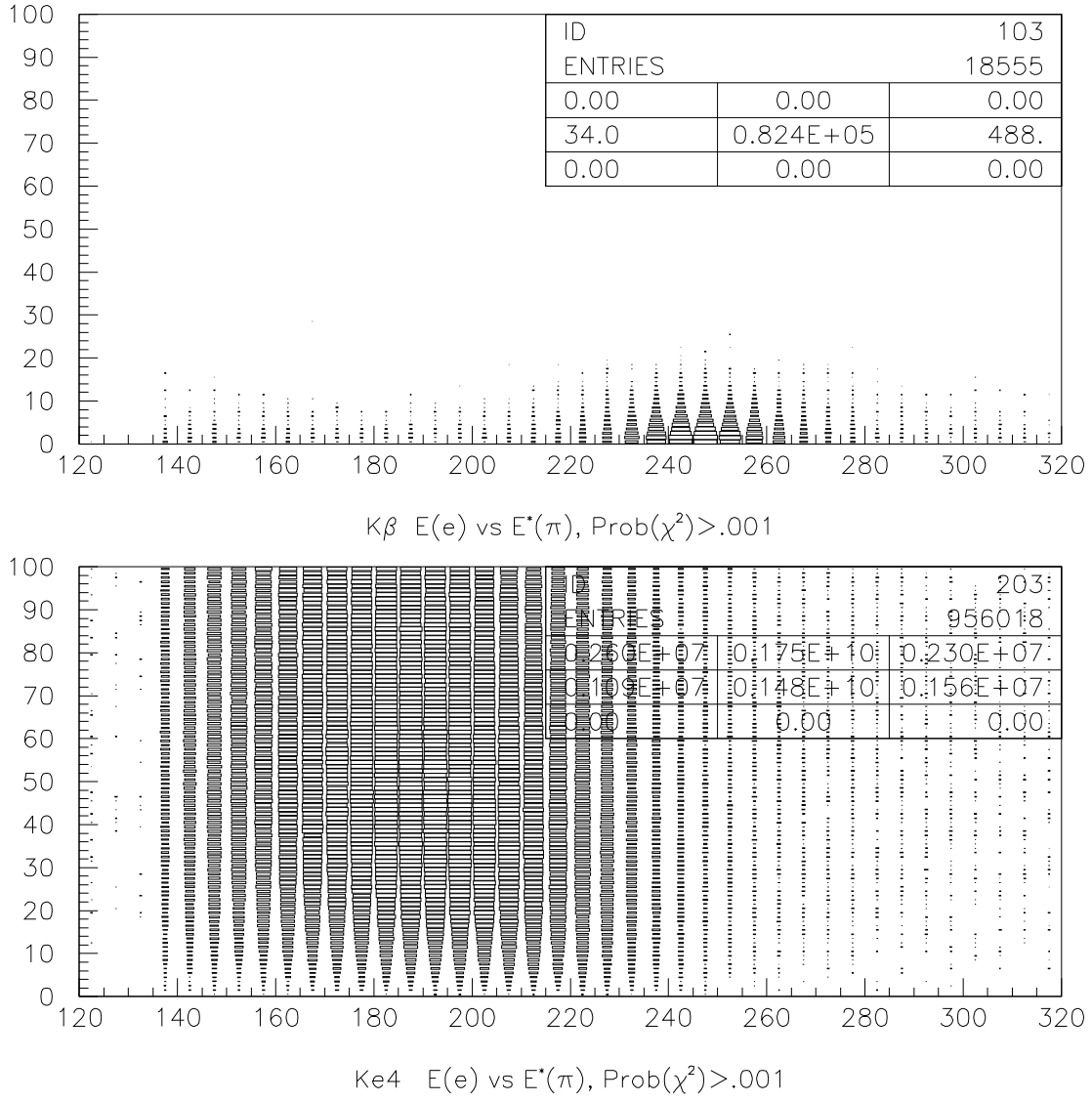
Figure 3: Upper: $E(e)$ *vs* $E^*(\pi^0)$ distribution for $K_L^0 \to K^\pm e^\mp \nu$ decays. Lower: $E(e)$ *vs* $E^*(\pi^0)$ distribution for $K_L^0 \to \pi^0 \pi^\pm e^\mp \nu$ decays. The reconstructed K_L^0 vertex is required to be in the range $1065 < Z < 1415$ cm. The probability of χ^2 for the fit to the K_L^0 vertex is required to be > 0.001. No other cuts are applied.
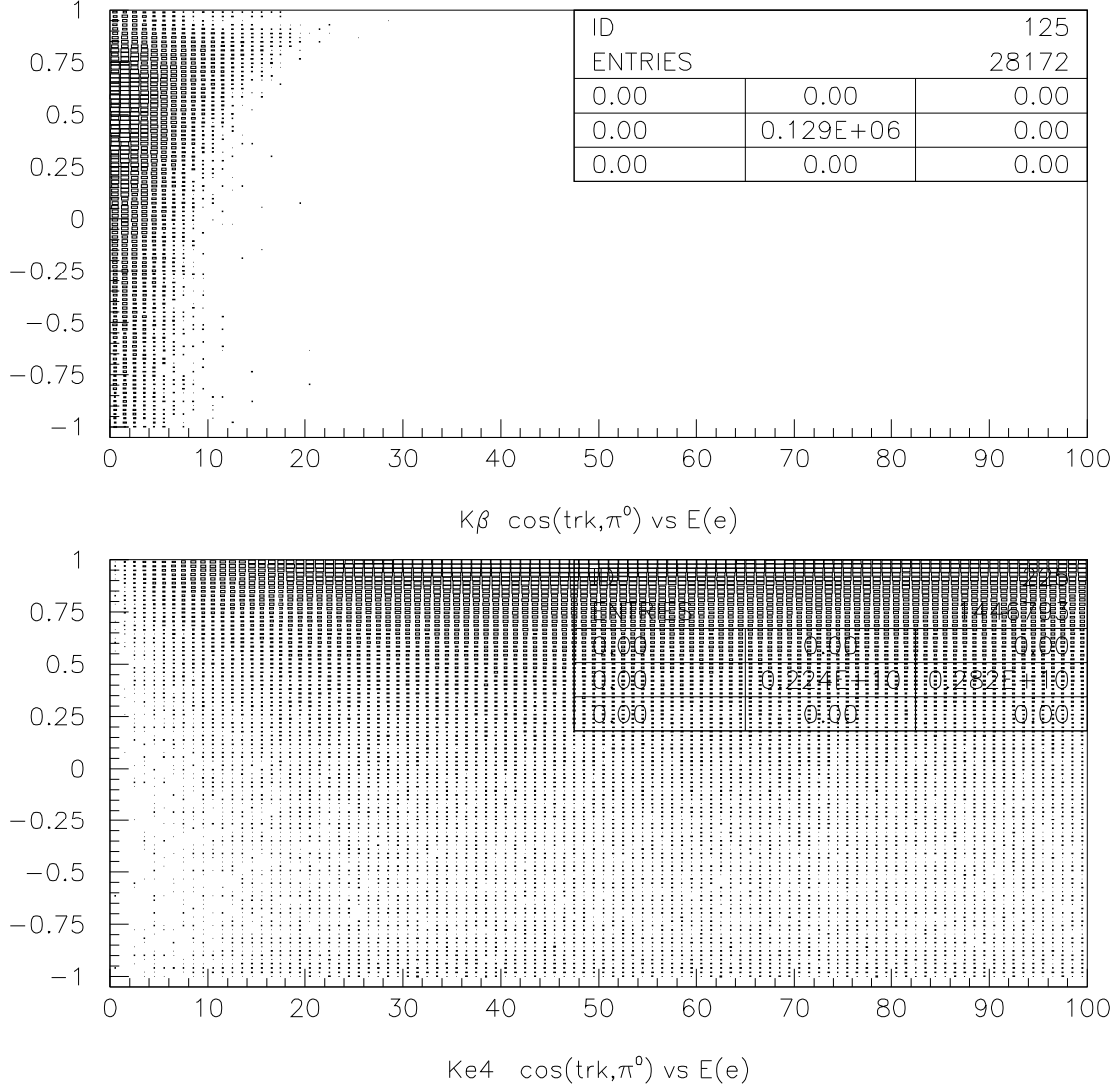
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Figure 4: Upper: $\cos(\pi^\pm, \pi^0)$ *vs* $E(e)$ distribution for $K_L^0 \to K^\pm e^\mp \nu$ decays. Lower: $\cos(\pi^\pm, \pi^0)$ *vs* $E(e)$ distribution for $K_L^0 \to \pi^0 \pi^\pm e^\mp \nu$ decays. The reconstructed K_L^0 vertex is required to be in the range $1065 < Z < 1415$ cm. The probability of χ^2 for the fit to the K_L^0 vertex is required to be > 0.001. No other cuts are applied.
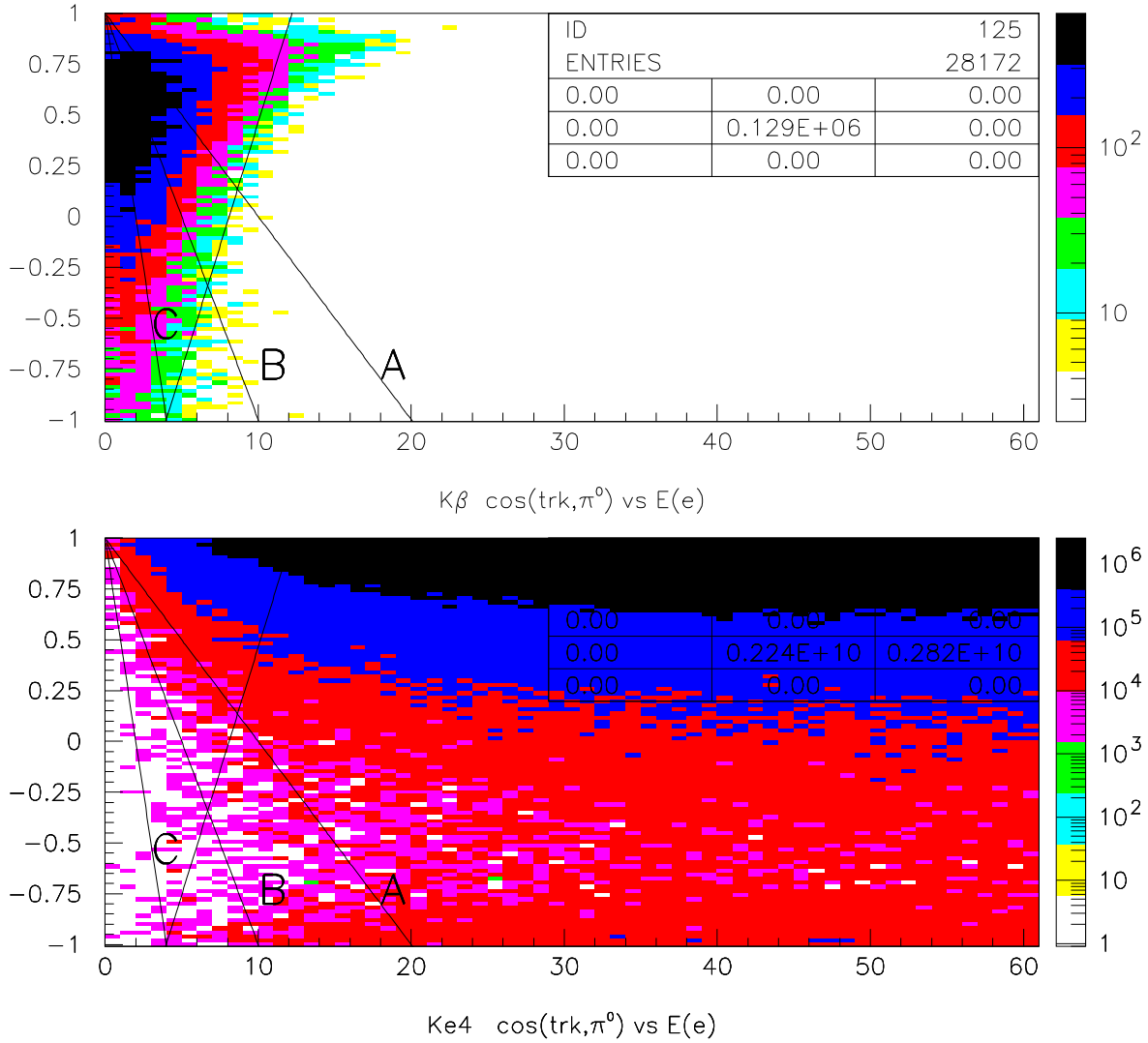
Kβ cos(trk,π⁰) vs E(e)

Ke4 cos(trk,π⁰) vs E(e)

Figure 5: Upper: $\cos(\pi^\pm, \pi^0)$ *vs* $E(e)$ distribution for $K_L^0 \to K^\pm e^\mp \nu$ decays. Lower: $\cos(\pi^\pm, \pi^0)$ *vs* $E(e)$ distribution for $K_L^0 \to \pi^0 \pi^\pm e^\mp \nu$ decays. The z scale is logrithmic. The solid lines show different cuts used to select signal. All signal events are required to be to the left of the line that originates from the lower right corner. Signal events are also required to be to the left of the lines labelled "A", "B" or "C". The resulting yields of $K_L^0 \to \pi^0 \pi^\pm e^\mp \nu$ and $K_L^0 \to K^\pm e^\mp \nu$ for these three cuts are shown in Figure 6. The reconstructed K_L^0 vertex is required to be in the range $1065 < Z < 1415$ cm. The probability of χ^2 for the fit to the K_L^0 vertex is required to be > 0.001. No other cuts are applied.

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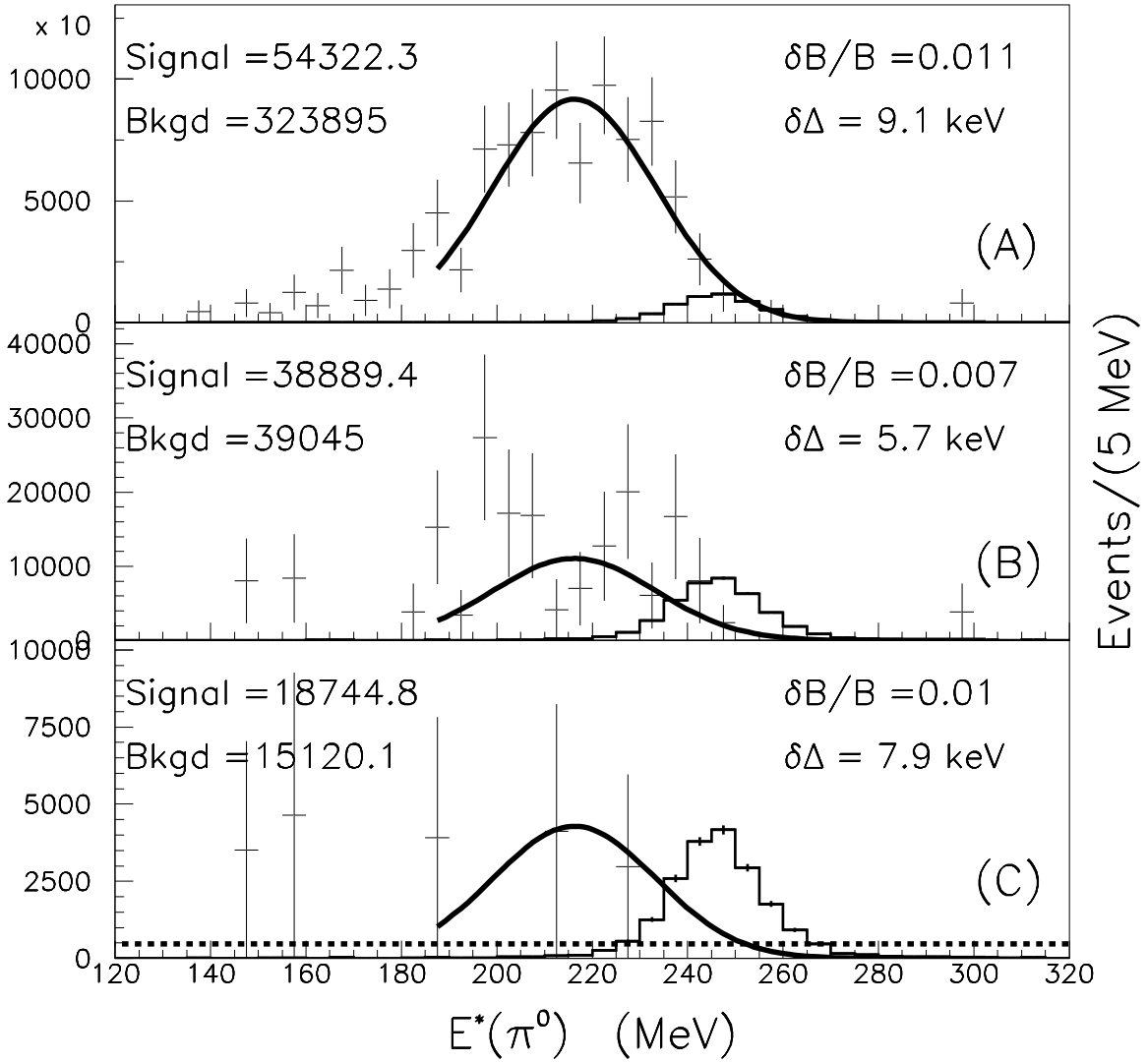
Figure 6: The $E^*(\pi^0)$ distribution for $K_L^0 \to \pi^0 \pi^\pm e^\mp \nu$ (points with error bars) and $K_L^0 \to K^\pm e^\mp \nu$ (histogram) for the three cuts labelled "A", "B" and "C" shown in Figure 5. The curve is a gaussian fit to estimate the background in the signal region. The mean and the width of the gaussian for the two lower plots are fixed to the fitted mean and width for the upper plot. The dashed line in the lower plot shows the result of a 0th order polynomial fit to the background. The number of signal and background events in the range $220 < E^*(\pi^0) < 270$ MeV is given in the upper left of each plot. The fractional statistical uncertainty on $\mathcal{B}(K_L^0 \to K^\pm e^\mp \nu)$ and the statistical uncertainty in the mass difference is given in the upper right of each plot.